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13. ABSTRACT (Maximum 200 words)

The purpose of this Phase I program was to investigate a compact and efficient laser source in the 430nm violet spectral range using frequency-doubling of a cw single-mode AlGaAs diode laser in an external resonant doubler constructed of potassium niobate. The primary objective of the Phase I program was to develop and evaluate a novel monolithic frequency-doubler design. Another goal was to eliminate the need for an optical isolator.

Several monolithic potassium niobate resonant doublers were constructed and tested with Fabry-Perot (F-P) and distributed-Bragg-reflector (DBR) diode lasers. Approximately 9mW of cw 430nm violet light was generated with the best doubler. The DBR laser was found to be more than 100 times less sensitive to feedback than the F-P diode laser, but neither laser provided stable frequency-doubled output in Phase I experiments.

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A Compact and Efficient Violet Laser Source

Phase I Final Report

February, 1995

1. Introduction

A. Background

The purpose of this Phase I program was to investigate a compact and efficient laser source in the 430nm violet spectral range using frequency-doubling of a cw single-mode AlGaAs diode laser in a monolithic external resonant doubler constructed of potassium niobate. This work was motivated by the need for compact, efficient and long-lived laser sources at shorter visible wavelengths for applications such as optical data storage, semiconductor inspection equipment and biomedical instrumentation.

Frequency-doubling with cw diode lasers is usually inefficient. For example, the second harmonic power that could be generated using a 100 milliwatt cw diode laser in a single pass through a 5mm long piece of potassium niobate is about 0.13 mW, which corresponds to a conversion efficiency of only 0.13%.

One effective way to increase frequency-doubling efficiency with cw diode lasers is to place the nonlinear material (potassium niobate) in a resonant optical cavity [1-3]. The circulating power, P_c, that can be established in the resonant cavity is related to the power, P_1, incident on cavity by:

$$P_c = P_1 (1 - r_1) [\ 1 - (r_1 r_m)^{0.5}\ ]^{-2} \qquad (1)$$

where r_1 is the input mirror reflectivity and r_m is given by:

$$r_m = T (1 - \Gamma P_c). \qquad (2)$$

In Equation (2), T is the round-trip transmission through the cavity and includes the transmission of the bulk of the potassium niobate crystal and Γ is the nonlinear conversion coefficient of the potassium niobate crystal. Γ is approximately 0.013 per Watt for a 5mm potassium niobate crystal.

By using an external resonant cavity, the second harmonic power, P_2, which will be generated in the potassium niobate crystal then varies as the square of P_c:

$$\mathbf{P_2 = \Gamma P_c^2} . \qquad \textbf{(3)}$$

rather than the square of P_1 and much higher conversion efficiencies can be accomplished. For example, if P_c is 10 times larger than P_1, 13 mW of second harmonic would be generated, corresponding to a conversion efficiency of 13%.

Because diode lasers are extremely sensitive to retro-reflected light, earlier work involved with frequency-doubling of cw diode lasers in resonant cavities has either used feedback from the doubler to control the frequency and spectral content of the diode laser [1,4,5] or utilized optical isolators between the diode laser and the resonant cavity to eliminate feedback to the laser [2,3]. The first approach is extremely sensitive to the level and the phase of return light. The second approach is less than optimal because optical isolators are relatively large compared to diode lasers and are relatively expensive. Also, optical isolators in the near-infrared spectral range tend to be lossy, reducing the amount of diode light available for frequency-doubling and reducing conversion efficiency. A goal of this Phase I program was to demonstrate a design that eliminated the need for an optical isolator.

B. Phase I Technical Objectives

To demonstrate the viability of a compact violet laser source using a cw diode laser and a monolithic frequency doubler without an optical isolator, the specific Phase I technical objectives were:

1: Design a monolithic potassium niobate frequency-doubler in the 430nm spectral range for cw single-mode AlGaAs diode lasers in the 100mW power range.

2: Design an optical coupling scheme to optimize collection of the output of a single--mode diode laser and mode-match it to the cavity mode of the monolithic doubler.

3: Measure the finesse of the doubler by tuning the diode laser frequency or the crystal temperature. Measure coupling efficiency and diode laser light retro-reflected from the monolithic doubler.

4: Frequency-lock the diode laser to the monolithic doubler and maximize violet light output. Measure conversion efficiency and amplitude stability.

5: Use the results of 1-4 above to optimize the design of the monolithic doubler.

6. Report the results of Phase I in a final report with recommendations for further development in Phase II.

The results of Phase I are presented in Section 2. Recommendations for further work are contained in Section 3.

2. Results

A. Monolithic Resonant Doubler Design

A number of factors enter into the optimum design of a resonant doubler. The key aspect of any efficient resonant doubler scheme is minimization of optical loss. This can be facilitated by minimizing the number of optical surfaces. The lowest loss resonant doubler cavities are monolithic, with the required optical surfaces fabricated directly on the nonlinear crystal [3]. The lowest loss reflective optical surfaces are clean, flat total-internal-reflection (TIR) surfaces.

Another source of optical loss in a monolithic resonant doubler is bulk scatter and absorption. These losses can be minimized by reducing the path length in the crystal. The disadvantage to shorter crystal length is that the nonlinear conversion coefficient, Γ, is also correspondingly reduced. The optimum crystal length and mirror coating reflectivity were determined by estimating the crystal loss and using Equations (1) - (3).

In Phase I, monolithic potassium niobate doublers were fabricated using the geometry shown in Figure 1. Resonators were fabricated and coated at Virgo Optics, Port Richey, Fl. Each monolithic doubler consisted of two flat TIR surfaces and a single curved surface polished directly onto a potassium niobate crystal. The curved surface was optically coated. The three optical surfaces defined a triangular beam path in the crystal. Resonators were fabricated so that one of the longer legs of this triangular beam path was parallel to the a-axis of the potassium niobate. The c-axis of each crystal was perpendicular to the largest surfaces of the doubler. The total path length in the Phase I design was 13mm. The radius of curvature of the coated surface was 25mm. The reflectivity of the coated surface was 93%. The resonators were 4mm thick.

The resonator dimensions, mirror coating reflectivity and optical losses define the free spectral range (FSR) and finesse of the resonators. The FSR for the potassium niobate doublers with 13mm path length was about 10.3GHz. The finesse of the resonant ring cavity, F, is related to the optical losses of the crystal and coating by the following expression:

$$\mathbf{F = \pi[R]^{1/2}\,[1 - R]^{-1}} \qquad \mathbf{(4)}$$

where,

$$\mathbf{R = [r_1 r_2 r_3 T]^{1/2}} \qquad \mathbf{(5)}$$

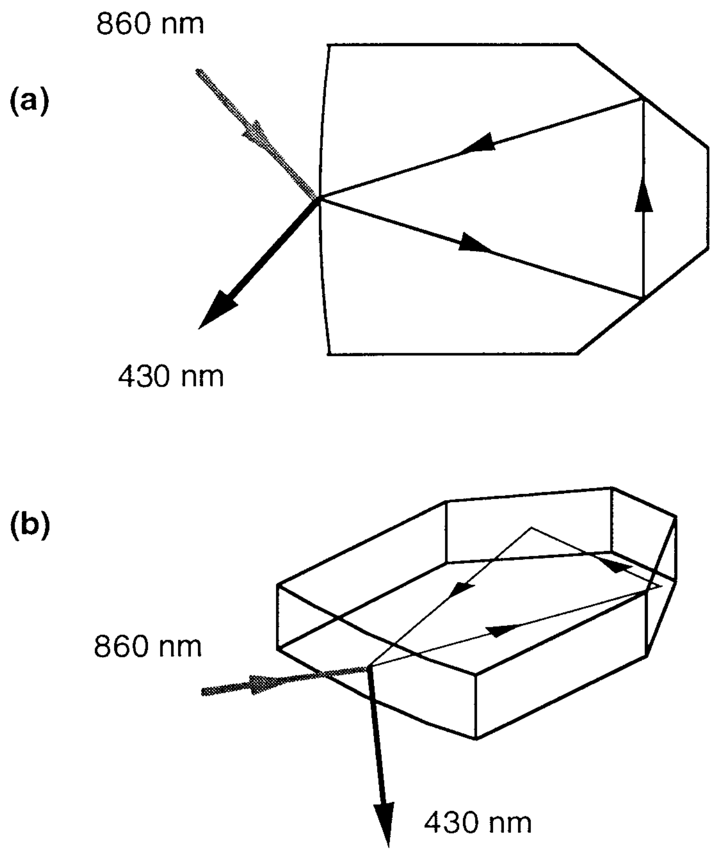

Figure 1: Schematic Diagram of Monolithic Potassium Niobate Resonant Ring Frequency-Doubler. Part (a) shows a top view; Part (b) shows an isometric view.

and the r's are the reflectivities of the mirrors (two TIRs and one coated) and T is the transmission through the bulk of the crystal. For a crystal resonator with 2% bulk loss (T = 0.98) and an output coupler with reflectivity of 0.93, the expected finesse was 68. The full-width-half-maximum of an individual resonance, FSR/F, was expected be about 152MHz. This is large compared to the expected spectral width of single-frequency diode lasers to be used in this work.

B. Diode Laser Characteristics

Two different single-mode 100 mW AlGaAs diode lasers in the 860nm spectral range from SDL were obtained and evaluated in Phase I. The first diode laser was a conventional Fabry-Perot (F-P) device (SDL 5411-G1). The threshold for this device was about 30mA. The variation of the output wavelength of this laser as a function of diode current was measured using a Burleigh Wavemeter and is shown in Figure 2. The diode tuned at a rate of approximately 1.0GHz per mA. The output power variation over the range from 100mA to 120mA was 75 mW to 96 mW. The temperature tuning rate for this diode laser was 0.355nm per degree Centigrade.

The second diode laser evaluated in this program was a distributed Bragg reflector (DBR) laser (SDL 5712-H1). This device differed from the more conventional Fabry-Perot device in that one of the reflectors is a grating structure near the active region on the AlGaAs chip, rather than a cleaved mirror. The DBR was expected to be more stable in frequency and more resistant to optical feedback than the Fabry-Perot laser. The output frequency of the DBR laser vs diode current is shown in Figure 3. Wavelength tuning of the DBR with diode current was similar to that of the F-P device. The output wavelength was 852nm at 28°C. The temperature tuning rate of this device was 0.078nm per °C.

The output of the F-P diode laser was diffraction-limited, with a source size of about 1μm in one dimension by about 3μm in the other. The rapidly diverging light from the diode laser was collected using a short focal length molded asphere lens from Corning (Model #350230, focal length = 4.5mm). The collimated output beam of the F-P laser was analyzed with a beam analysis instrument (Merchantek PC Beamscope) and was found to be well fit to a Gaussian distribution. The beam was measured to have a spot size ($1/e^2$ radius) of 0.52mm in the vertical dimension and a spot size of 1.67mm in the horizontal dimension. The nearly 1:3 aspect ratio of the output beam was consistent with expectation. The aspect ratio of the beam was adjusted to about 1:1.5 by passage of the beam through a pair of Littrow prisms (Optima 420-1212-830).

The output beam of the DBR laser was not as clean as the output of the F-P laser. The beam seemed to be clipped in the horizontal dimension. The collimated output of the DBR laser was well fit to a Gaussian in the verical dimension.

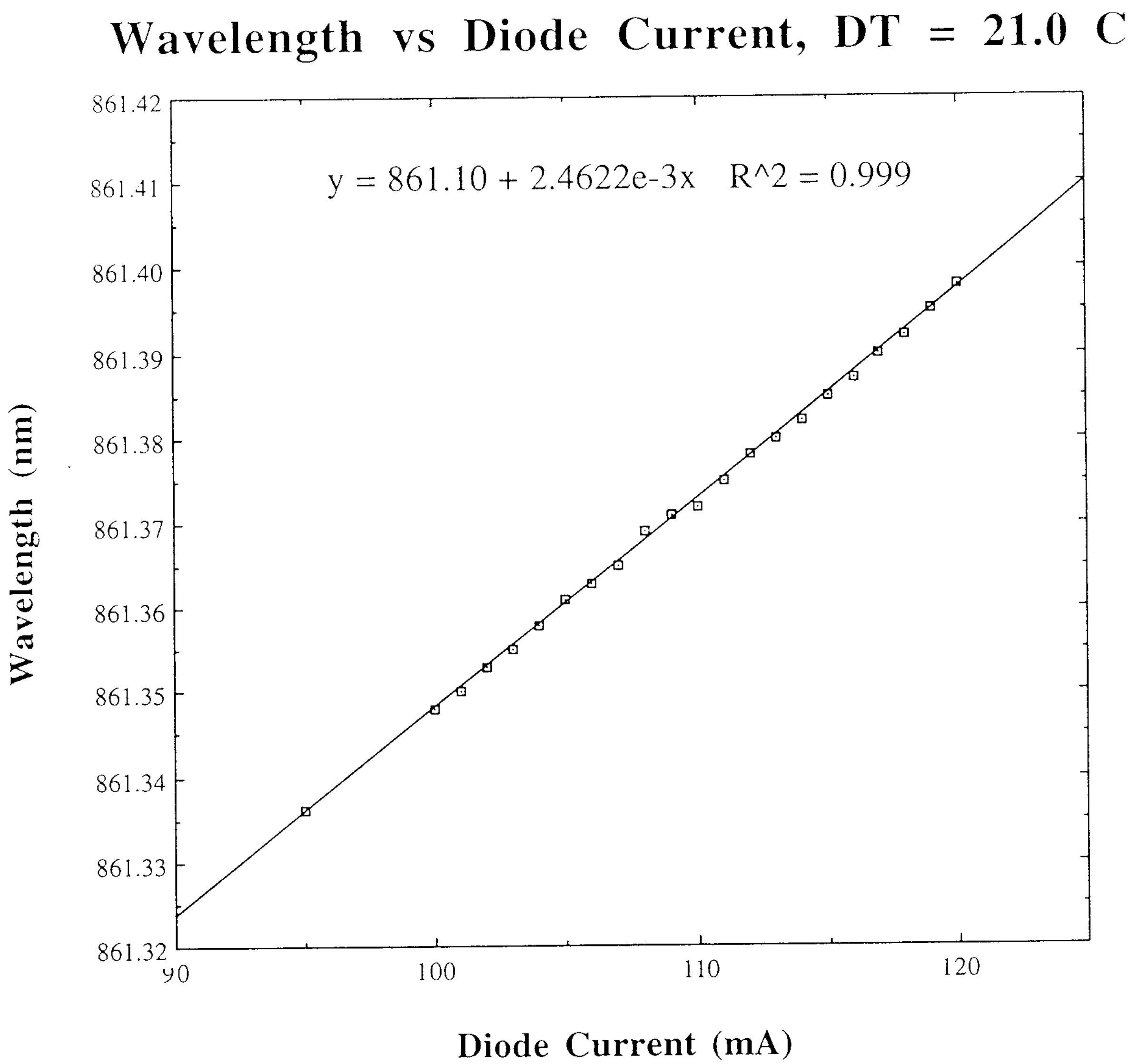

Figure 2: Wavelength Tuning of Fabry-Perot Single-Frequency Diode Laser (SDL 5411-G1) versus Diode Current.

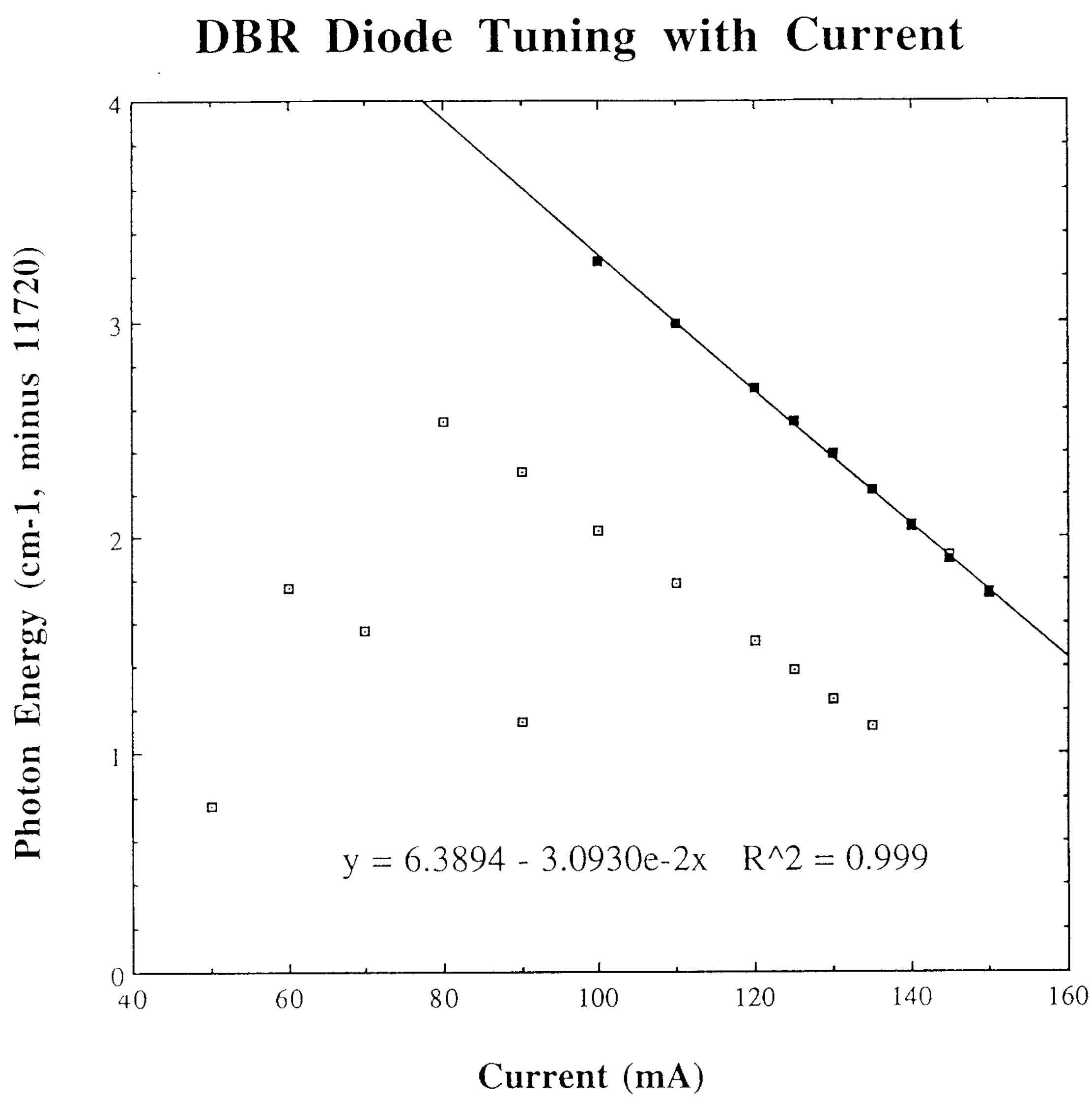

Figure 3: Frequency Tuning of Distributed Bragg Reflector (DBR) Single-Frequency Diode Laser (SDL 5712-H1) versus Diode Current.

The collimated output of the diode lasers was focused with a 100mm focal length spherical lens into a 3mm long potassium niobate crystal to determine the phase-matching characteristics. The temperature of the crystal was scanned slowly to determine the phase-matching temperature. A phase-matching curve for this crystal and the F-P diode laser is shown in Figure 4. The second harmonic output for the F-P laser operating at 861nm was maximized at a crystal temperature of 29.0°C with a full-width-half-maximum of 0.9°C. Approximately 21 μW of 430nm light was generated in a single pass through the 3mm crystal. This corresponded to a nonlinear conversion coefficient of 0.0021 per Watt for the 3mm long crystal. The output of the 852nm DBR laser phase-matched near 0°C.

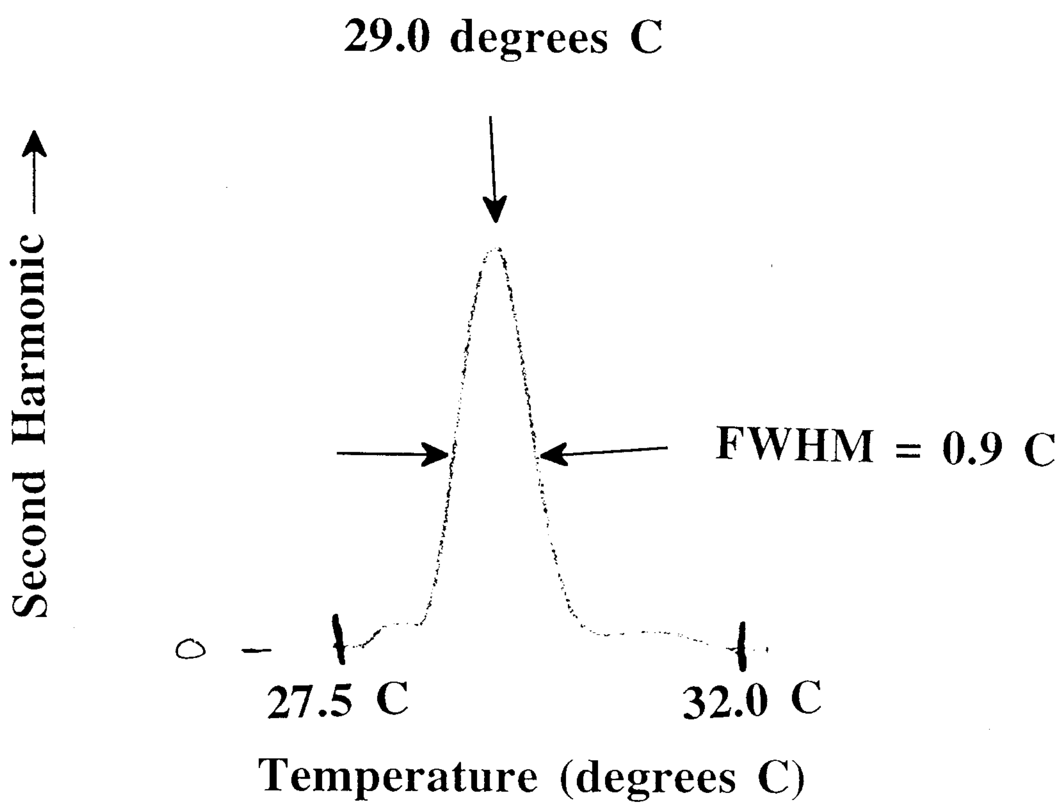

Figure 4: Phase-Matching Curve for Frequency-Doubling of a Single-Frequency Diode Laser in a 3mm Long Potassium Niobate Crystal versus Crystal Temperature.

C. Monolithic Resonant Doubler Evaluation

Monolithic potassium niobate doubler crystals were fabricated and coated by Virgo Optics. After fabrication and coating, the doublers were mounted in Fluorosint holders to reduce stresses of the crystals during handling. Stressing of potassium niobate crystals can lead to depoling of the crystals. The monolithic doubler crystals were initially evaluated using a helium-neon laser to verify the accuracy of the fabrication.

Next, the output of the F-P diode laser was mode-matched into the crystals using the collimating and focusing lenses and the two Littrow prisms. The finesse of the doublers was measured by scanning the diode laser current and measuring the variation of diode light reflected from the doublers. From the measured tuning rate for the F-P diode laser and the calculated FSR of 10.3GHz for the doublers, it was possible to scan two free-spectral-ranges of the doublers by scanning the diode current about 20mA, from 100mA to 120mA. Continuous frequency tuning with no mode hops was observed over this range (see Figure 2).

Values of finesse measured for doublers ranged from 20 to 27.5. These values are much lower than expected. A finesse of 27.5 implies a product of mirror reflectivity and crystal transmission of 0.785. For a mirror reflectivity of 0.93, the implied bulk crystal loss is about 15%. Inserting these values into Equations (1) - (3) leads to a predicted second harmonic power of 0.7 mW. It seems likely that finesse measurements were complicated by thermal effects which have been observed by several researchers [2,6]. Absorption of the diode laser light by the potassium niobate probably lead to a small localized heating of the monolithic resonators, resulting in frequency shifting as the diode laser frequency was shifted through resonance. A strong correlation between finesse and 430nm power was observed, indicating at least qualitative agreement with theory. Another possible cause for low values of finesse was that the spectral content of the diode laser output was comparable to the spectral width of an individual resonance. For a finesse of 27.5 and a free-spectral-range of 10.3GHz, the width of an individual resonance is about 375 MHz.

A key aspect of this Phase I program was determination of the amount of diode laser light re-directed by the monolithic doubler geometry back to the diode laser and the effect of this retro-reflected light on the diode laser. The level of retro-reflected diode light was measured by inserting an uncoated microscope slide at 45^{o} between the beam shaping prisms and the focusing lens. The level of return light was measured as the diode

laser frequency was tuned through resonance. The return light level was normalized to the incident diode power.

With 35% of the diode laser light incident on the best doubler crystal coupled into the crystal, approximately 2 parts in 10^5 were re-directed to the diode laser with the diode laser frequency on resonance with the monolithic doubler. This on-resonance return signal compared to a off-resonance background approximately 4 times, probably due to an imperfect anti-reflection (AR) coating on the mode-matching lens.

The sensitivity of the F-P diode laser and DBR laser to feedback were measured. The output of each laser was collimated and passed through a prism to reflect some of the output to a photodiode. The light transmitted through the prism was retro-reflected to the diode with a flat high-reflector (HR) mirror. Neutral density filters were placed between the prism and the HR to vary the feedback level. The amplitude stability of each diode laser was measured with the photodiode as a function of feedback.

The F-P laser was very sensitive to feedback. Noise on the laser output was detected for feedback as low as 2 parts in 10^5. This level was the same order of magnitude as resonant retro-reflection from monolithic doublers, but also feedback from passive elements such as collimating lenses. The DBR laser was much less sensitive to feedback and no additional noise was detected on the output of this laser for feedback as large as 1%.

D. Frequency Doubling Experiments

The preliminary single-pass frequency-doubling experiments with the F-P and DBR diode lasers showed that the potassium niobate doublers needed to be heated to about 28°C for the 861nm F-P laser and cooled to about 0°C for the 852nm DBR laser. The monolithic doublers were mounted on an oven assembly for frequency-doubling with the F-P laser and on a thermo-electric cooler (TEC) for frequency-doubling with the DBR laser. The doubler and TEC assembly were purged with flowing dry air to prevent condensation on the doubler crystals.

Each laser and doubler combination was roughly aligned using the infrared light and then the alignment and crystal temperature were fine-tuned by maximizing the second harmonic power. Residual diode laser light was separated from the second harmonic using an absorption filter. In each case the violet 430nm output of the resonant doubler was an oval TEM_{00} beam with an aspect ratio of about 1.5 to 1. The measured transmission of the coatings on the doubler crystals was 87.5%. As a result, the violet output from the doublers actually consisted of an array of spatially distinct spots with 87.5% of the power in the primary beam.

The best doubler combined with the F-P diode to produce 9.4 mW of violet output in the main output beam. Only 35% of the 95 mW output of the diode laser was coupled into doubler. The violet output was very noisy and very sensitive to alignment of the system. The poor coupling of the diode laser into the doubler was possibly due to inexact alignment of the diode to the doubler or to inadequate match of the spectral output of the diode laser to the resonance of the doubler. Substantially less violet light was produced with the other doubler crystals, and less than 1.0 mW was generated with the doubler with the lowest finesse.

The best doubler combined with the DBR diode laser to generate 3.0 mW of violet output. This occurred with 75 mW of 852nm light incident on the doubler and only about 33% coupled into the crystal. The poor optical coupling in this case was partially due to the poor output beam quality of the DBR diode laser.

3. Conclusions and Recommendations for Future Research and Development

This Phase I program was only partially successful. Monolithic potassium niobate resonant doublers were fabricated and used to produce >9 mW of cw 430nm light. While feedback from these doublers to the diode lasers was less than one part in ten thousand, this was sufficient to destabilize the diode laser output. Consequently, it was not possible to produce stable 430nm violet output without an optical isolator.

While unsuccessful from the point of view of elimination of the optical isolator, the monolithic potassium niobate resonant doublers are substantially more compact than discrete element resonant doubler designs. Further development efforts could lead to compact and stable frequency-doubled diode laser sources which incorporate these monolithic doublers and optical isolators.

This Phase I program also demonstrated that DBR lasers were substantially more resistant to optical feedback than Fabry-Perot diode lasers. Further investigation of these lasers for frequency-doubling seems warranted because they are intrinsically less sensitive to feedback than Fabry-Perot diodes and the repeatability of output wavelength from batch-to-batch is expected to be better. This latter feature significantly simplifies commercially implementation of the these devices since the unit-to-unit phase-matching temperature would be more consistant. While DBR lasers currently cost more than F-P lasers, the price differential should decrease with higher production volume.

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